

Figure 34. Consolidated underfrequency droop test results. *Illustration from NREL*

#### 4.2.2 Frequency Droop Tests during Overfrequency Event

Frequency droop tests for the overfrequency events were also conducted on August 24, 2016. The results of one 5% droop test on the morning on August 24, 2016, are shown in Figure 35. The plant's response to the overfrequency event was measured at the plant's POI. The calculated active power time series shows that the plant decreased its power output during the initial grid frequency increase, then gradually returned to its original pretest level as frequency returned to its normal pre-fault level. The droop response of the plant from several tests can be observed in the X-Y plots shown in Figure 36 (a and b) and Figure 37, wherein a linear dependence between frequency and measured power can be observed once the frequency deviation exceeded the deadband. The plant demonstrated consistent and accurate down-regulation performance during all overfrequency droop tests.

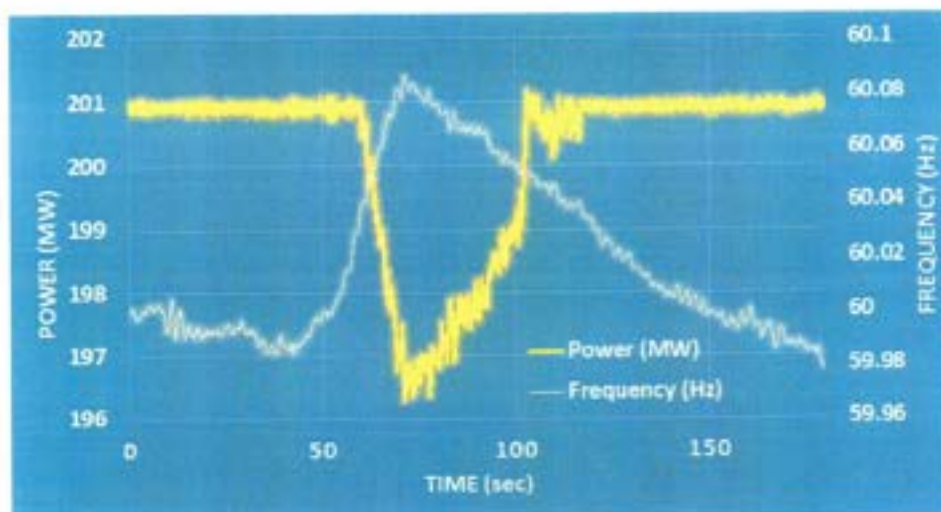


Figure 35. Example of the plant's response to an overfrequency event (5% droop test during sunrise). *Illustration from NREL*

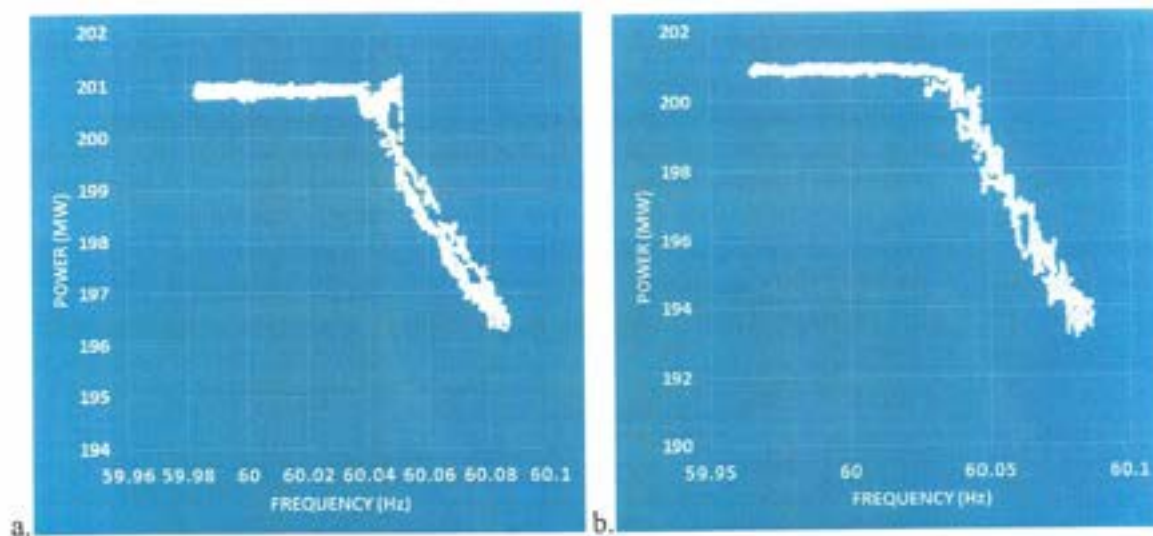
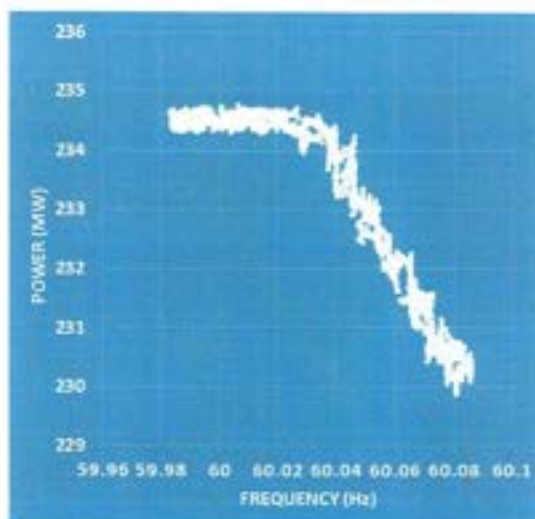
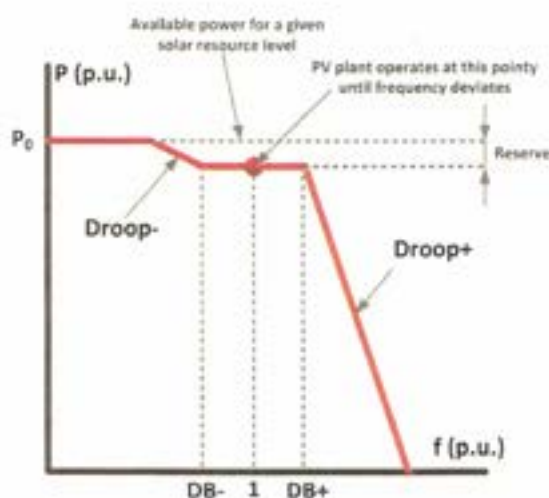


Figure 36. Measured droop characteristics for an overfrequency event: (a) 5% droop test and (b) 3% droop test during midday. *Illustration from NREL*



**Figure 37. Measured droop characteristics for an overfrequency event (5% droop test during sunset). Illustration from NREL**

A PV plant must operate in curtailed mode to provide enough reserve for PFR response during underfrequency conditions. During normal operating conditions with near-nominal system frequency, the control is set to provide a specified margin by generating less power than is available from the plant. The reserve available (i.e., headroom) is the available power curtailed, which is shown as the reserve between the operational point and  $P_0$  in Figure 38. If required by reliability consideration, a nonsymmetric droop curve is possible with solar PV power, depending on system needs, as shown in Figure 38. More aggressive droops (e.g., 1% or 2%) can be implemented for overfrequency regulation because PV plants are able to provide very fast curtailment. This type of nonsymmetric droop response will likely be demonstrated in future stages of this testing project.



**Figure 38. Concept of nonsymmetric droop characteristic for PV plants. Illustration from NREL**

## 5 Reactive Power and Voltage Control Tests

### 5.1 Rationale and Description of Reactive Power Tests

Voltage on the North American bulk system is normally regulated by generator operators, which are typically provided with voltage schedules by transmission operators [17]. The growing level of penetration of variable wind and solar generation has led to the need for them to contribute to power system voltage and reactive regulation because in the past the bulk system voltage regulation was provided almost exclusively by synchronous generators. According to FERC's LGIA [18], the generally accepted power factor requirement of a large generator is  $\pm 0.95$ . In conventional power plants with synchronous generators, the reactive power range is normally defined as dynamic, so synchronous generators need to continuously adjust their reactive power production or absorption within a power factor range of  $\pm 0.95$ . For PV power plants, the reactive power requirements are not well defined. FERC Order 661-A [19] is applicable to wind generators but sometimes applied to PV plants as well. It also requires a power factor range of  $\pm 0.95$  measured at the POI and requires that the plant provide sufficient dynamic voltage support to ensure safety and reliability (the requirement for dynamic voltage support is normally determined during interconnection studies). Utility-scale wind power plants are designed to meet the  $\pm 0.95$  power factor requirements; however, the common practice in the PV industry is to configure PV inverters to operate at unity power factor. It is expected that similar interconnection requirements for power factor range and low-voltage ride-through will be formulated for PV in the near future. To meet this requirement, PV inverters need to have MVA ratings large enough to handle full active and reactive current.

In its recent Order 827, FERC issued a final rule requiring all newly interconnecting nonsynchronous generators, including wind generators, to design their facilities to be capable of providing reactive power [20]. The generating facilities need to be capable of maintaining a composite power delivery at continuous rated power output at the high side of the generation substation at  $\pm 0.95$  power factors.

Conventional synchronous generators of power plants have reactive power capability that is typically described as a "D curve," as shown in Figure 39. The reactive power capability of conventional power plants is limited by many factors, including their maximum and minimum load capability, thermal limitations due to rotor and stator current-carrying capacities, and stability limits. The ability to provide reactive power at zero loads is usually not possible with many large plant designs. Only some generators are designed to operate as synchronous condensers with zero active loads. The reactive power capability of a PV inverter is determined by its current limit only. With proper MW and MVA rating, the PV inverter should be able to operate at full current with reactive power capability, similar to the one shown in Figure 39. In general, for the same MVA rating, a PV power plant is expected to have much superior reactive power capability than a conventional synchronous generator-based plant, as indicated notionally in Figure 39. In principle, PV inverters can provide reactive power support at zero power, similar to a STATCOM (see definition in [21]); however, this functionality is not standard because PV inverters are disconnected from the grid at night.

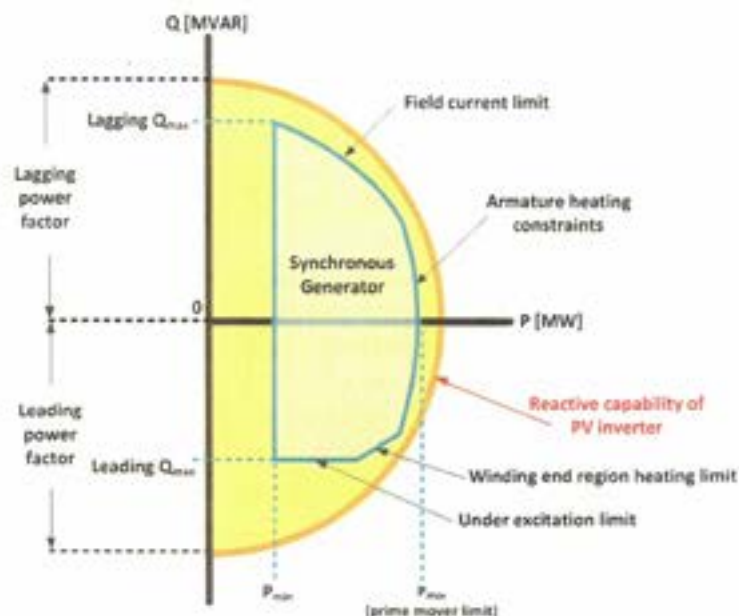


Figure 39. Comparison of reactive power capability for a synchronous generator and PV inverter of the same MVA and MW ratings. *Illustration from NREL*

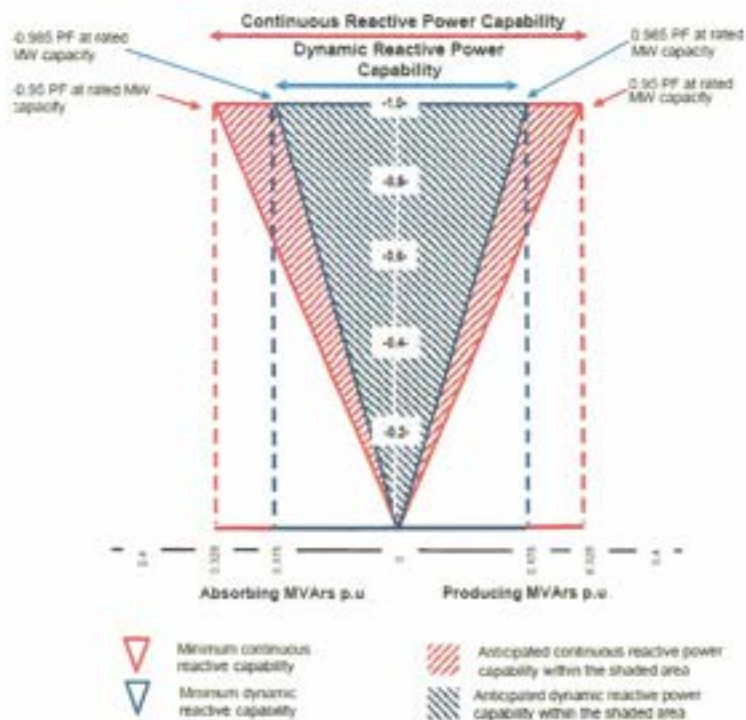


Figure 40. Proposed reactive power capability for asynchronous resources. *Illustration from CAISO*

In its proposed reactive power capability characteristic for asynchronous generation (Figure 40), CAISO defined the requirements for dynamic and continuous reactive power performance by such resources [21]. The red vertical lines shown in Figure 40 represent the expected reactive capability of the asynchronous generating plant at the high side of the generator step-up bank. At all levels of real power output, the plant is expected to produce or absorb reactive power equivalent to approximately 33% of the plant's actual real power output. For example, at the plant's maximum 300-MW real power capability, the expected dynamic reactive capability should be 100 MVARS lagging or 100 MVARS leading. Also, at 50% real power output, the expected reactive capability should be 50 MVARS lagging or 50 MVARS leading, and at zero MW output, the expected reactive output should be zero. Figure 41 shows the expected reactive capability of the 300-MW PV plant under test if it must comply with the proposed CAISO requirement for asynchronous generating facilities at the POI. The PV plant is supposed to absorb or produce 100 MVAR of reactive power when operating at full MW capacity at a power factor of -0.95 or +0.95, respectively.

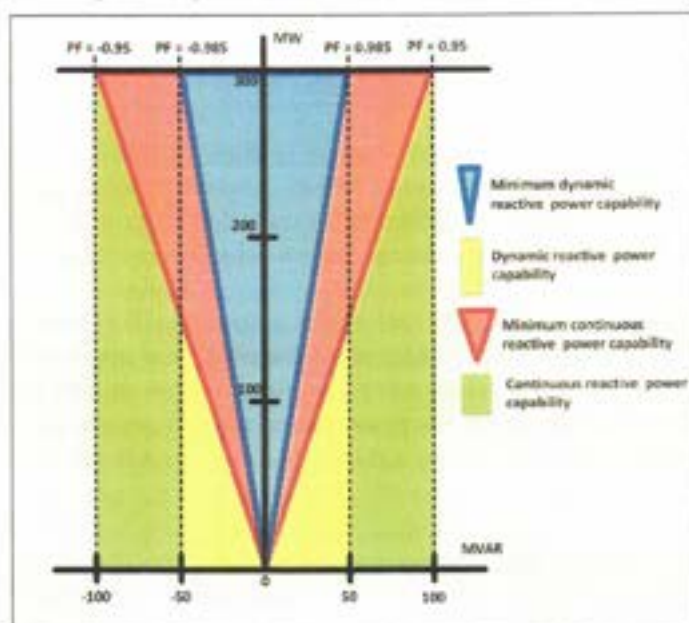


Figure 41. CAISO's proposed reactive capability applied to the 300-MW PV plant under testing.  
Illustration from NREL

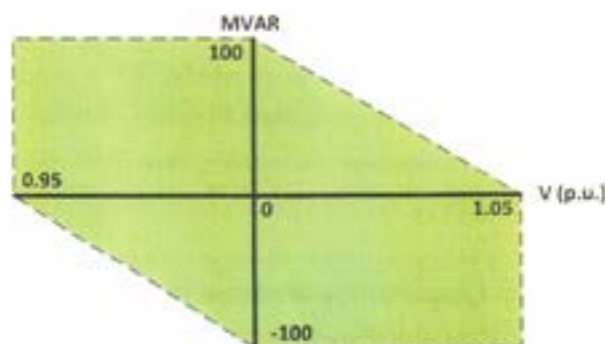


Figure 42. The plant's reactive power capability at different voltage levels at full MW output.  
Illustration from NREL

The voltage at the POI may change because of grid conditions, but the plant must maintain its reactive power capability. For this purpose, CAISO's proposed reactive power requirement specifies a voltage operating window for the asynchronous generating facility to provide reactive power at 0.95 lagging power factor when voltage levels are between 0.95–1 p.u. at the POI. Likewise, it should be able to absorb reactive power at 0.95 leading power factor when voltage levels are between 1–1.05 p.u. The proposed capability at different voltage levels applied to the 300-MW PV plant at its full production level is shown in Figure 42.

CAISO proposed adopting a uniform requirement of asynchronous inverter-coupled resources to provide reactive power capability and voltage regulation, as shown in Figure 40 [21]. According to CAISO's draft proposal on reactive power and financial compensation, the asynchronous generating facility shall have dynamic and continuous reactive capability for power factor ranges of  $\pm 0.985$  and  $\pm 0.95$ , respectively. Through its initiative, CAISO has explored mechanisms to compensate resources for the capability and provision of reactive power. In some regions transmission providers make payments for reactive power capability, but not all. These regions conclude that requiring the capability for this operation is a good utility practice and a necessary condition for conducting normal business [21], [22].

The primary objective of the reactive power test was to demonstrate the capability of the PV plant to operate in the voltage regulation mode within the power factor range of 0.95 leading/lagging. The plant controller maintained the specified voltage set point at the high side of the generator step-up bank by regulating the reactive power produced by the inverters.

The tests were conducted at three different real power output levels: (1) maximum production during the middle of the day, (2) during sunset when the plant is at approximately 50% of its maximum capability, and (3) during sunset when the plant is close to zero production. Measurements were conducted to verify the plant's capability to absorb and produce reactive power in accordance with Figure 40, within a range of  $\pm 100$  MVAR during various levels of real power output.

- The plant was first tested at its maximum real power output for a given irradiance level. At maximum real power output, the plant must demonstrate that it can produce approximately 33% of real output as dynamic reactive. Similarly, at maximum real power output, the plant must demonstrate that it can absorb approximately 33% of its real power output as reactive output.
- During sunset, as solar production drops off to approximately 50% of the resource's maximum capability, the plant must demonstrate that it can produce and absorb approximately 33% of its real power output as dynamic reactive output.
- During sunset, as the plant production approaches zero MW, the plant must demonstrate that it can produce and absorb approximately 33% of its real power output as dynamic reactive output.

## 5.2 Results of Reactive Capability Power Tests

The plant's reactive power capability was tested at two different power levels on August 23, 2016, and August 24, 2016. First, the plant's reactive power capability was measured during a number of tests when the plant was producing high levels of active power (250 MW and more).

Then the reactive power capability was measured at extremely low levels of MW production (less than 5 MW). The results of both tests are consolidated in a graph showing MVAR compared to MW, Figure 43, wherein the blue dots represent the data points measured by the plant's PMUs. The measurements are compared to the proposed CAISO reactive power requirement for asynchronous generation (yellow triangle), demonstrating that the plant meets the expected reactive power capability. In addition, the plant is capable of producing and absorbing reactive power at close to zero power production. Another, more articulate view of the same test results is shown in a three-dimensional view in Figure 44, which combines measured MW, MVAR, and POI voltage, allowing for the positioning of measured data points with respect to the proposed CAISO requirements.

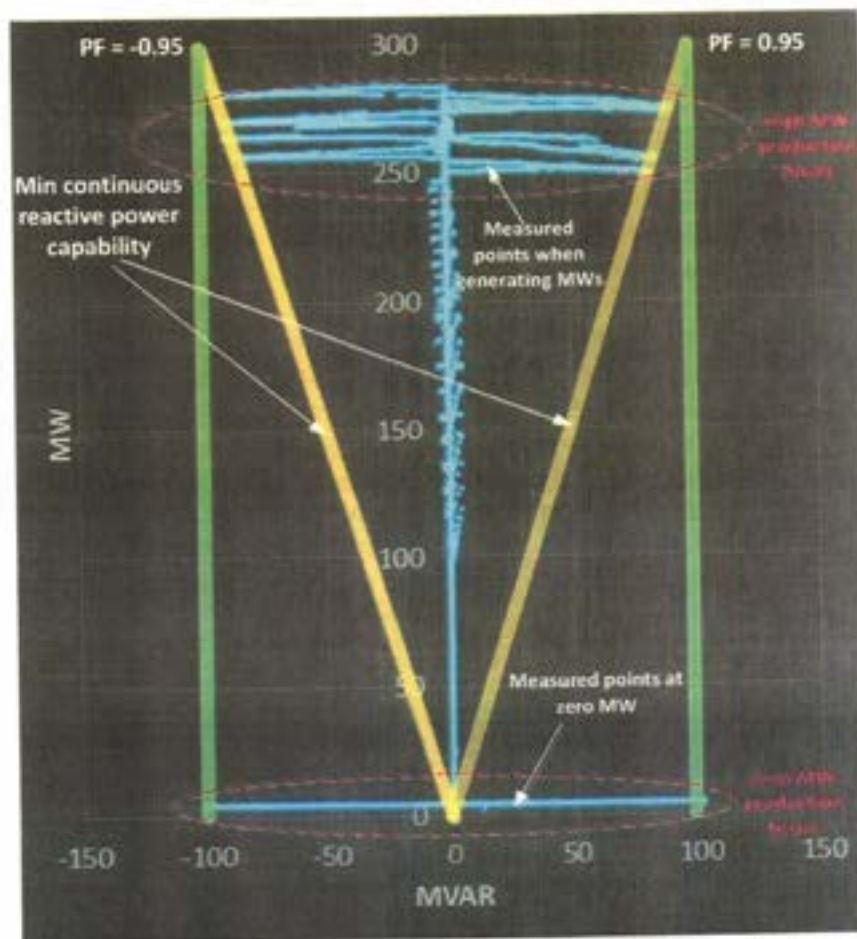
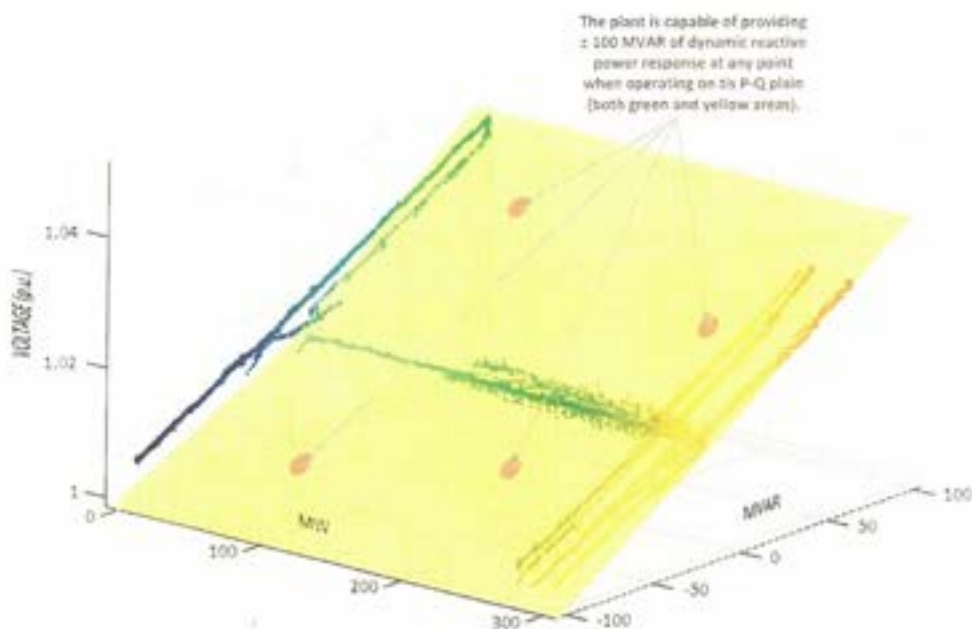
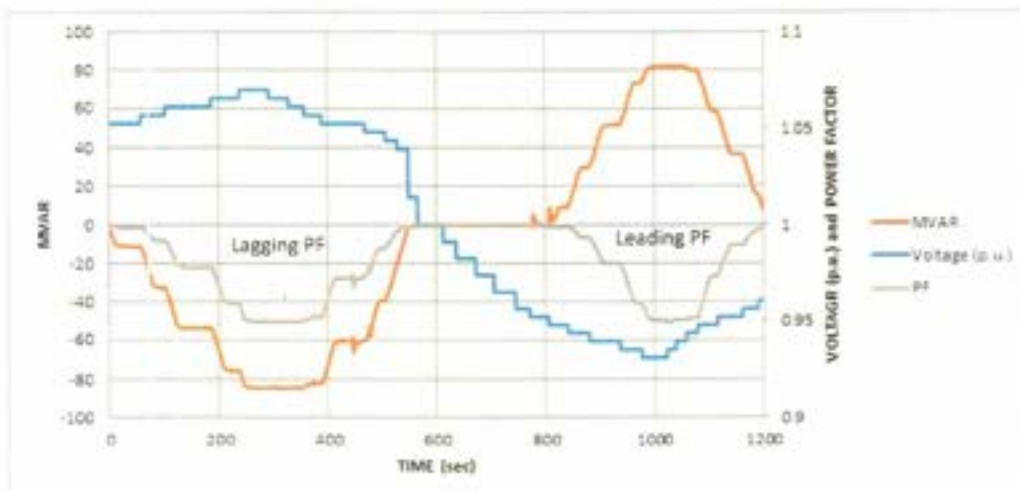


Figure 43. Measured reactive power capability at the POI. *Illustration from NREL*



**Figure 44. Measured reactive power capability and voltages at the POI. Illustration from NREL**

The voltage limit control test was conducted to verify the ability of the plant's control system capability to maintain a power factor target at the same time as maintaining voltage at the POI between the low and high limits (0.95 p.u. and 1.05 p.u., respectively), as shown in Figure 45. First, the plant was operating at nearly maximum active power generation in close to unity power factor control mode. An artificial POI voltage signal was provided to the plant controller to override the real measurement. While in power factor control mode, the control automatically switched to voltage limit mode to maintain the voltage within safe operating limits. Upon completion of the POI voltage increase or decrease with the power factor near the unity value, the control system switched back to power factor control mode.



**Figure 45. Results of the voltage limit control test. Illustration from NREL**

The same test is shown in Figure 46, wherein the measured reactive power is compared to the reactive power capability window from Figure 42. As shown in Figure 46, the plant is fully capable of operating within CAISO's proposed window at  $PF=\pm 0.95$ .

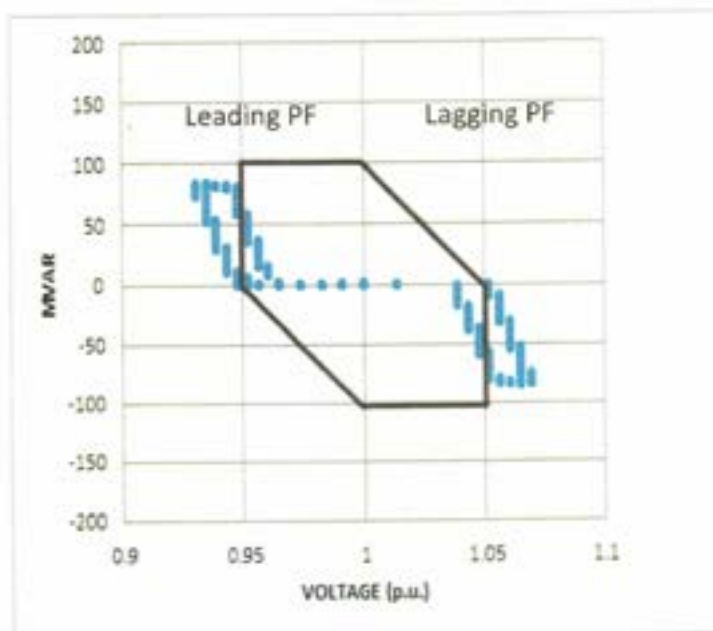
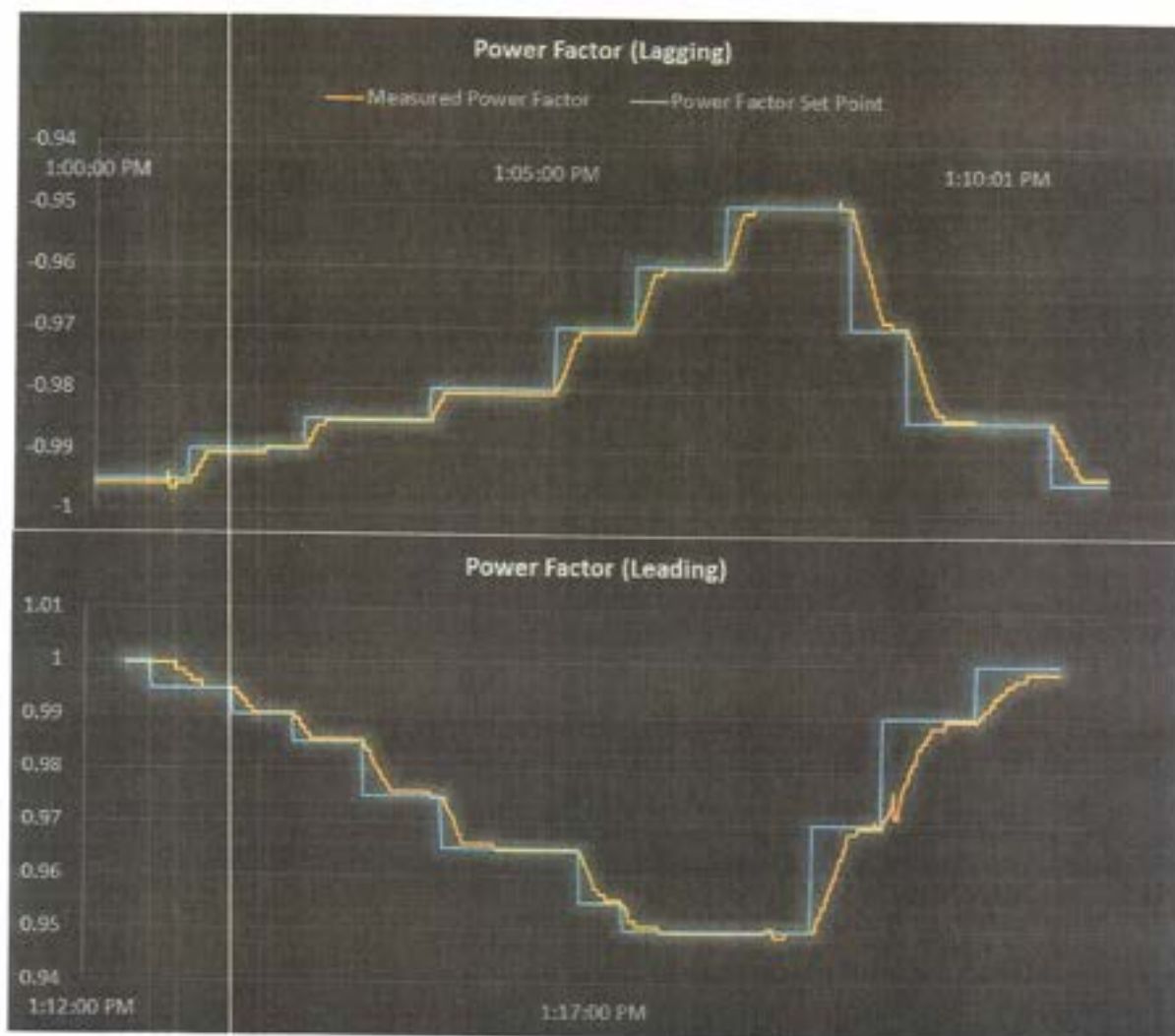


Figure 46. Voltage limit control test and reactive power capability. *Illustration from NREL*

In addition, the plant was tested to demonstrate the control operation in power factor control mode and characterize control system response to changes in power factor set point. Reactive power ramp rates and power factor limits for this test were specified at  $\pm 100$  MVAR/min and  $\pm 0.95$ , respectively. The results of the leading and lagging power factor control tests are shown in Figure 47. For both tests, the system was operating at nearly full power output. It reached its power factor targets with specified ramp rates in the PPC without any oscillation and stability issues.



**Figure 47. Lagging and leading power factor control tests. Illustration from First Solar**

Results of the reactive power set point control test are shown in Figure 48. This test was conducted during a period of high power generation, and it was intended to demonstrate the ability of the plant to maintain capacitive or inductive VARs at the POI. As shown in Figure 48, the plant was fully capable of following the reactive power set points with prescribed PPC reactive power ramp rates.

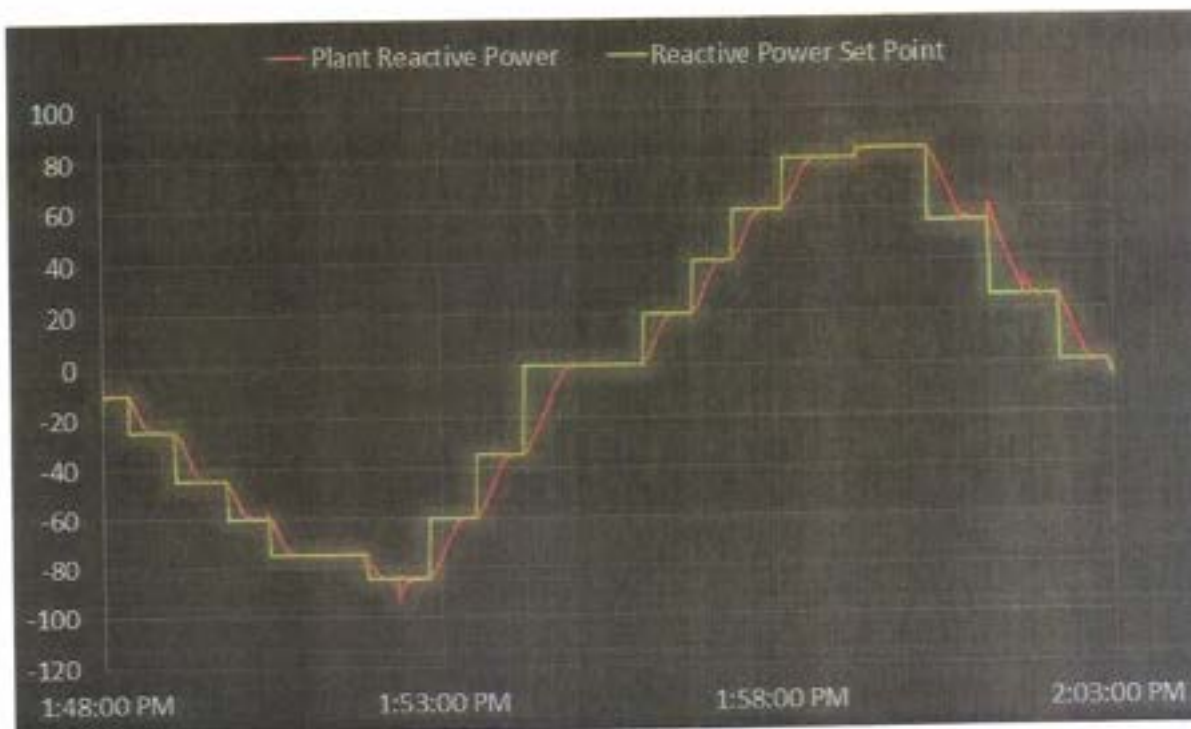


Figure 48. Reactive power control test. *Illustration from First Solar*

### 5.3 Low-Generation Reactive Power Production Test

One way to increase the optimal utilization of PV power plants is to use their capability to provide VAR support to the grid during times when the solar resource is not available. For this purpose, the capability of the grid-tied inverters of the 300-MW PV plant to provide reactive power support during a period of no active power generation was demonstrated. Due to the limited time window available for this testing, it was not possible to test this capability during dark hours of the day; instead, the team decided to demonstrate the VAR support capability of the plant at nearly zero active power generation. The plant's active output was curtailed to nearly zero MW on August 24, 2017. Then the command was sent to the plant controller to ramp the reactive power to produce or absorb 100 MVAR. The results of these tests along with the measured POI voltage are shown in Figure 49. The plant was fully capable of producing or absorbing the commanded MVAR levels during the whole testing time. Note that the conditions of this test are only partially realistic because special control schemes are needed for grid-tied inverters to operate as STATCOM when a PV array is fully de-energized, and a certain amount of active power needs to be drawn from the grid to compensate for inverter losses. A more realistic test for nighttime VAR mode is planned for the near future.

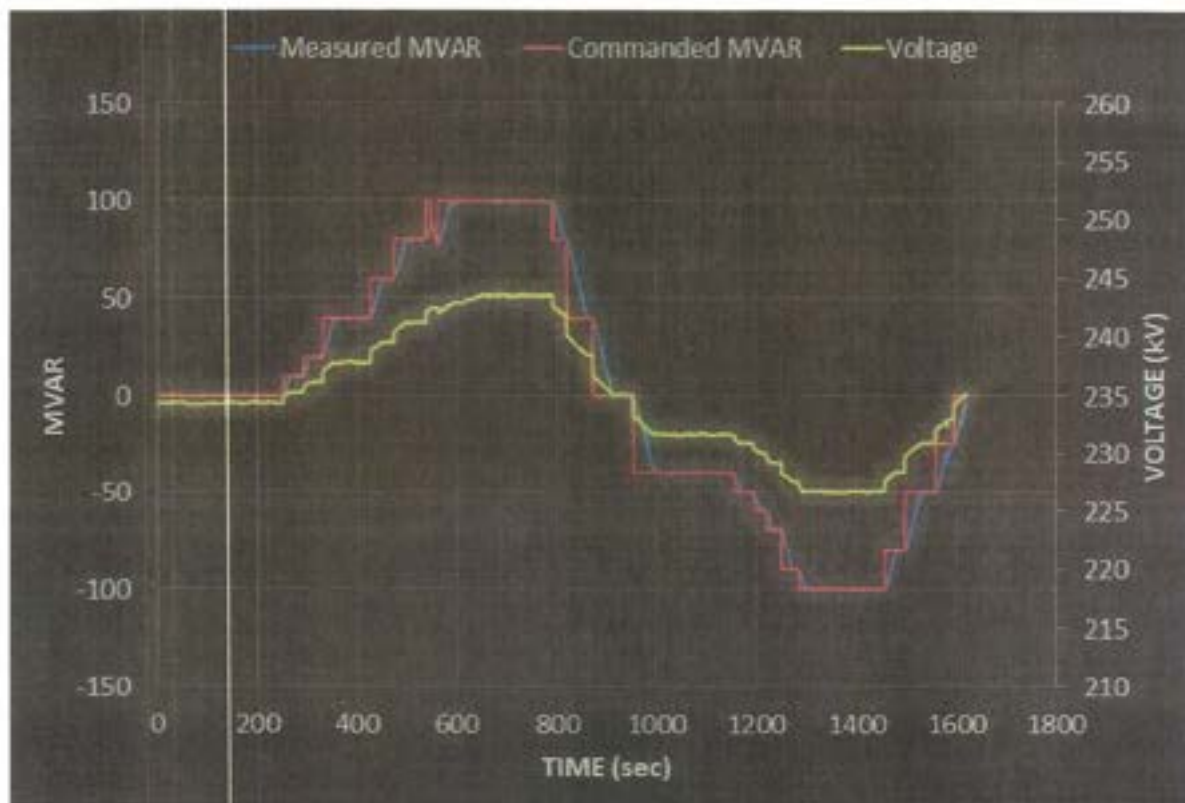


Figure 49. Reactive power production test at no active power ( $P \approx 0$  MW). Illustration from NREL

## 6 Additional Tests

The time series of the plant's measured active and reactive power and POI voltage for the whole period of testing on August 23, 2016, is shown in Figure 50. This summary combines results of several commissioning tests conducted between 10 a.m. and 3 p.m. on August 23, 2016. The tests conducted in the morning were related to various forms of APC, and the tests conducted in the afternoon involved various forms of reactive power, voltage, and power factor controls.

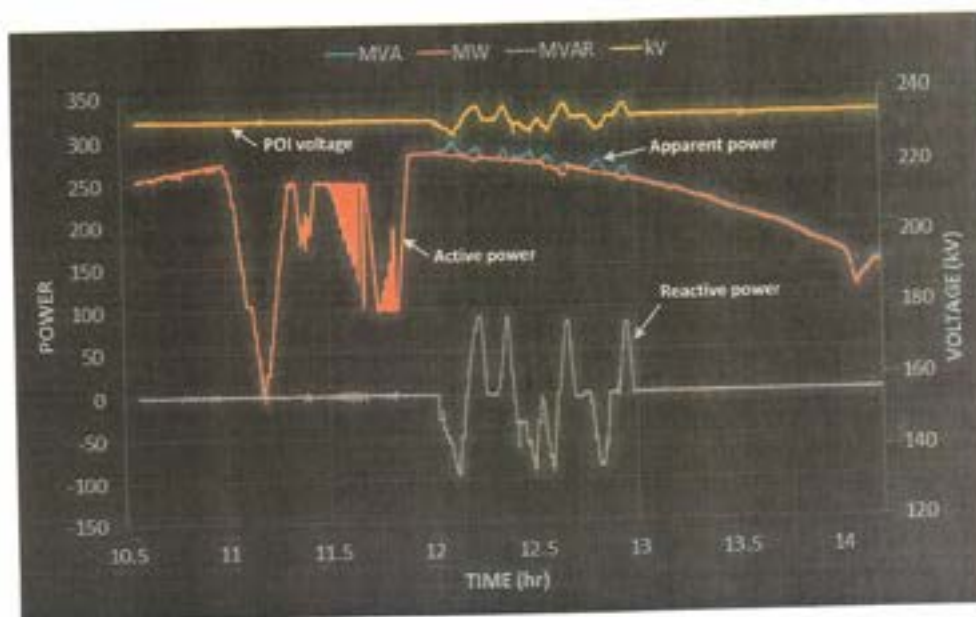


Figure 50. Plant output during the August 23, 2016, tests. Illustration from NREL

The curtailment control test was conducted to demonstrate the plant's ability to limit its active power production and then restore it to any desired level. The results of the test are shown in Figure 51. The plant was accurately following the active power set point from a nearly full production level to the zero level with a preset ramp rate of 30 MW/min. The plant's active power was then commanded to increase in accordance with the increasing set points. Note that the reactive power of the plant remained unchanged at a level of nearly zero MVAR for the whole range of active power. This is an indicator of the PV inverters' capability to independently control active and reactive power.

The curtailment control test also demonstrates that PV generation can provide additional ancillary services in the form of spinning and nonspinning reserves. According to CAISO's definitions, spinning reserve is a standby capacity from generation units already connected or synchronized to the grid and that can deliver their energy in 10 minutes when dispatched. With a demonstrated 30-MW/min ramp rate capability, the PV plant under test is capable of deploying 300 MW of spinning reserve in only 10 minutes for some hypothetical case of full curtailment. Nonspinning reserve is capacity that can be synchronized to the grid and ramped to a specified load within 10 minutes. Similarly, the PV plant can provide nonspinning reserve as well. In fact, in a PV plant, unlike any conventional generation, there is no differentiation between spinning and nonspinning reserve capacity due to the nature of PV generation.

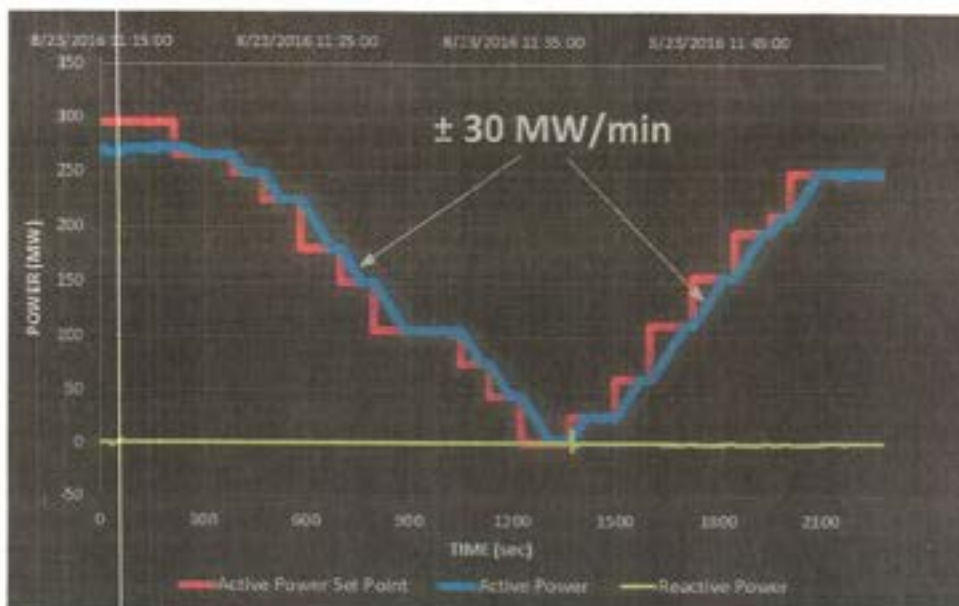


Figure 51. Results of the active power curtailment test. *Illustration from NREL*

Another type of APC test, called frequency validation, was conducted to demonstrate the control system response to frequency disturbances. Unlike the frequency droop tests described in Section 4 of this report, the frequency validation tests were conducted with artificially commanded step changes in POI frequency. Figure 52 shows the plant's response to the commanded frequency values. The plant's response corresponds to a 5% frequency droop setting with an excellent match between the measured and calculated target power levels. (All active power ramp rates in the PPC were bypassed when the plant is in frequency regulation mode.)

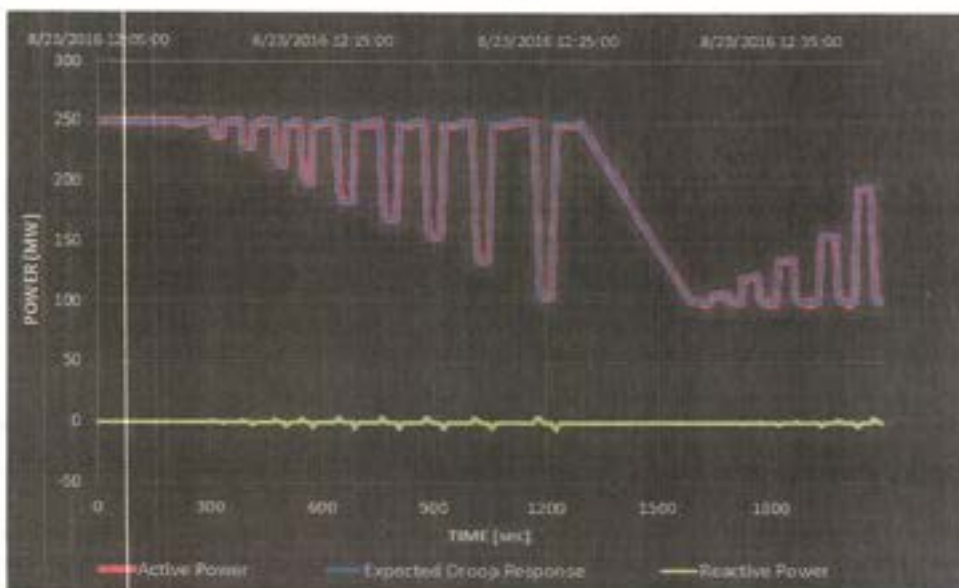


Figure 52. Results of the frequency validation test. *Illustration from NREL*

## 7 Conclusions and Future Plans

This project demonstrated how solar PV generating plants can provide a wide range of essential reliability services. Tests showed fast and accurate PV plant response to AGC, frequency, voltage, power factor, and reactive power signals under a variety of solar conditions.

### 7.1 Test Summary

The focus of this project was on demonstrating the controls of a 300-MW utility-scale PV power plant within CAISO's footprint to provide various types of active and reactive power controls for ancillary services.

Active power control capabilities for inverter-connected plants such as PV power plants have been acknowledged and available for a number of years; however, many of these capabilities have not been proven in a real, commercially operational setting by interfacing with the plant's operator on the ground as well as the system operator (either utility off-taker or transmission system operator).

This project is a result of collaboration among NREL, CAISO, and First Solar; NREL's participation was funded through DOE's Solar Energy Technologies Office. The project team gained valuable real experience for all industry players regarding (1) a PV power plant's implementations of these capabilities, (2) the system operators' interface and communications acceptance of measured plant parameters and use of the parameters, (3) the iterative loop for the system operators to send back appropriate set points, (4) the logic of the PV PPCs to respond to the set points, and (5) the PV power plant's return of up-to-date information (such as available peak plant power) to complete the iterative loop.

The AGC tests demonstrated the plant's ability to follow CAISO's AGC dispatch signals during three different solar resource intensity time frames: (1) sunrise, (2) middle of the day (noon–2 p.m.), and (3) sunset. For this purpose, the plant was curtailed by 30 MW from its available peak power to have maneuverability to follow CAISO's AGC signal. During these tests, fast and accurate AGC performance was demonstrated at different solar resource conditions.

For the frequency response tests, the plant was also operated in curtailed mode to have enough headroom to increase its output in response to a frequency decline outside of a defined deadband. Headroom is achieved by sending a curtailment command to the PPC after initially computing its estimation of maximum capability using real-time solar irradiance data from the network of pyranometers, real-time measurements of panel and inverter data, and other static characteristics of the system's components. Assuming that the plant will be reimbursed for the energy loss due to curtailment for these ancillary services, it is likely that the maximum power estimation will need to be refined and validated. The plant demonstrated fast and accurate frequency response performance for different droop settings (3% and 5%) under various solar resource conditions for both underfrequency and overfrequency events.

The plant also demonstrated the ability to operate in three modes related to reactive power control: voltage regulation, power factor regulation, and reactive power control. The plant can operate in only one of the three modes at a time, with a seamless transition from one mode to another. The plant controller was able to maintain the specified voltage set points at the POI by

regulating the reactive power produced or absorbed by the PV inverters. Also, the plant's ability to produce or absorb reactive power at nearly zero MW production (STATCOM mode) was demonstrated as well.

## 7.2 Detailed Conclusions

General conclusions include the following:

- Advancements in smart inverter technology combined with advanced plant controls allow solar PV resources to provide regulation, voltage support, and frequency response during various operation modes.
- Solar PV resources with these advanced grid-friendly capabilities have unique operating characteristics that can enhance system reliability, like conventional generators, by providing:
  - Essential reliability services during periods of oversupply
  - Voltage support when the plant's output is near zero
  - Fast frequency response (inertia response time frame)
  - Frequency response for low as well as high frequency events.
- Accurate estimation of available peak power is important for the precision of AGC control.
- It makes sense to include specifications for such available peak power estimations into future interconnection requirements and resource performance verification procedures.
- System-level modeling exercises will be needed to determine the exact parameters of each control feature to maximize the reliability benefits to CAISO or any other system operator that will be utilizing such controls in its operations.
- All hardware components enabling PV power plants to provide a full suite of grid-friendly controls are already in existence in many utility-scale PV plants. Fully enabling these is mainly a matter of activating these controls and/or implementing communications upgrades. Issues to be addressed in the process include communications protocol compatibility and proper scaling for set point signals. Although these are not significant barriers, dialogue and interaction among the plant operators and the system operators is an important component of implementing APC capabilities. Modifying programming logic may be necessary at multiple places in the chain of communications.
- Fine-tuning the PPC to achieve rapid and precise responses might be a necessary step in many PV plants. It may be easier with newer equipment because of the faster response times of newer inverters and controller systems.
- Many utility-scale PV power plants are already capable of receiving curtailment signals from grid operators; each plant is different, but it is expected that the transition to AGC operation mode will be relatively simple with modifications made only to the PPC and interface software (Figure 53).
- Fast response by PV inverters coupled with plant-level controls make it possible to develop other advanced controls, such as STATCOM functionality, power oscillation

damping controls, subsynchronous controls oscillations damping and mitigation, active filter operation mode by PV inverters, etc.

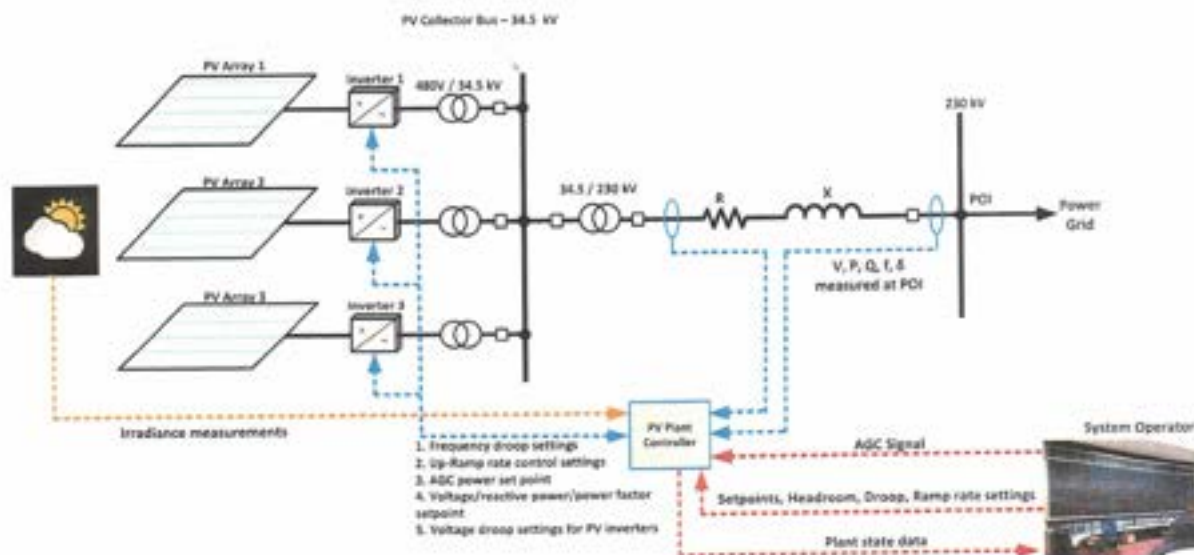


Figure 53. A grid-friendly PV power plant. Illustration from NREL

The project team conducted tests that demonstrated how various types of active and reactive power controls can leverage PV generation's value from being a simple variable energy resource to a resource providing a wide range of ancillary services. With this project's approach to a holistic demonstration on an actual large utility-scale operational PV power plant and dissemination of the obtained results, the team sought to close some gaps in perspectives that exist among various stakeholders in California and nationwide by providing real test data. If PV-generated power can offer a supportive product that benefits the power system and is economic for PV power plant owners and customers, this functionality should be recognized and encouraged.

### 7.3 Future Plans

Future plans by the project team include:

- Identifying potential barriers to providing essential reliability services to make these services operationally feasible
- Exploring economic and/or contractual incentives to maximize production and not hold back production to provide reliability services
- Identifying necessary steps to unlock opportunities to use reliability services from renewable resources by:
  - Assessing and quantifying the fleet's capability to provide reliability services
  - Evaluating policies such as FERC Notice of Inquiry RM16-6, which recommends requiring all synchronous and asynchronous machines to provide primary frequency response

- Considering how renewable resources already dispatched or curtailed can provide upward regulation and frequency response
- Identifying what tariff changes are necessary to remove barriers and allow variable energy resources to provide reliability services
- Exploring ways to allow inverter-based resources and associated control systems to be used to enhance reliability and response to frequency events
- Exploring further opportunities for inverter-based resources to participate in the various markets for energy and ancillary services.
- Developing further modifications to control algorithms and fine-tune control parameters for improved performance of the demonstrated services
- Demonstrating true PV STATCOM functionality during nighttime hours
- Demonstrating ancillary services by a number of PV plants within CAISO's footprint to understand the impacts of solar resource geographical diversity on the aggregate response by solar generation on various types of ancillary services
- Finally, CAISO and NREL are interested in exploring the possibility of conducting simultaneous demonstration testing of ancillary service controls by solar PV and wind generation to understand the aggregate response by two different renewable energy resources when providing various combinations of ancillary services.

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## Appendix: Test Plan

### Objective

Perform multiple tests, and document the performance of a 300-MW PV solar facility in a commercially operational setting. The plant currently has a maximum capacity of 299.9 MW and participates in the independent system operator's (ISO's) market. The plant is in the process of completing its final acceptance testing by mid- to late August 2016.

The California Independent System Operator (CAISO) is responsible for ensuring that sufficient ancillary services are available to maintain the reliability of the grid controlled by the ISO. Modern utility-scale PV power plants consist of multiple power electronic inverters and can contribute to grid stability and reliability through sophisticated "grid-friendly" controls. The findings of this testing project will provide valuable information to the ISO concerning the ability of variable energy resources to provide ancillary services, enhance system reliability, and participate in future ancillary service markets in a manner that is similar to that of traditional generators. All tests would be done in a manner to minimize curtailment to the plant below its current commercial  $P_{max}$ . Curtailment details and actual test times would be worked out prior to the tests.

The project team—consisting of experts from CAISO, First Solar, and the National Renewable Energy Laboratory (NREL)—developed the demonstration concept and test plan to show how various types of active and reactive power controls can leverage PV generation's value from being a simple intermittent energy resource to providing a wide range of ancillary services. Through this demonstration and the subsequent dissemination of the results, the team will provide valuable real test data from an actual utility-scale operational PV power plant to all stakeholders in California and nationwide. If PV-generated power can offer a supportive product that benefits the power system and is economic for PV power plant owners and customers, this functionality should be recognized and encouraged.

### Regulation-Up and Regulation-Down

This test will demonstrate the plant's ability to follow the ISO's automatic generation control (AGC) dispatch signals. The purpose of AGC is to enable the power plant to follow the active power set point dispatched by the ISO at the end of every 4-second time interval. The ISO will conduct the test at three different solar resource intensity time frames: (1) sunrise, (2) middle of the day (noon–4 p.m.), and (3) sunset. Each test will provide actual 4-second AGC signals that the ISO has previously sent to a regulation-certified resource of similar size. Normally, CAISO measures the accuracy of a resource's response to energy management system signals during 15-minute intervals by calculating the ratio between the sum of the total 4-second set point deviations and the sum of the AGC set points.

- Sunrise

During sunrise, the plant would be instructed to operate within a real power range of *20 MW below its peak power capability*. Approximately 10 minutes of actual 4-second AGC signals would then be fed into the plant's controller, and the plant's response would be monitored.

- Middle of the day

During the middle of the day, the plant would be instructed to operate within a real power range of *20 MW below its peak power capability*. Approximately 20 minutes of actual 4-second AGC signals would then be fed into the plant's controller, and the plant's response would be monitored.

- **Sunset**

During sunset, the plant would be instructed to operate within a real power range of *20 MW below its peak power capability*. About 20 minutes of actual 4-second AGC signals would then be fed into the plant's controller, and the plant's response would be monitored.

### **Expectation**

During the test, the ISO will monitor the delayed response time of the plant (i.e., the time between the resource receiving a control signal indicating a change in set point and the instant the resource's MW output changes). The ISO will also monitor the accuracy of the plant's response to the regulation set-point changes. The data from this test will be used by ISOs in future resource-specific expected mileage for the purposes of awarding regulation-up and regulation-down capacity.

### **Curtailment**

It is expected that the plant would be curtailed by 20 MW for approximately 45 (3 x 15 minutes) minutes.

## **Voltage Regulation Control**

The ISO will test the plant in the voltage regulation mode, whereby the controller maintains a scheduled voltage at the terminal of the generator step-up transformer by regulating the reactive power produced by the inverters. The voltage regulation system is based on the reactive capabilities of the inverters using a closed-loop control system similar to automatic voltage regulators in conventional generators.

The reactive power capability would be tested to show the Federal Energy Regulatory Commission's (FERC's) proposed reactive capability (Order 827), which requires that all newly interconnecting nonsynchronous generators design their generating facilities to meet the reactive power requirements at all levels of real power output. (*Refer to the vertical red lines in Figure A-1.*)

### **Objective**

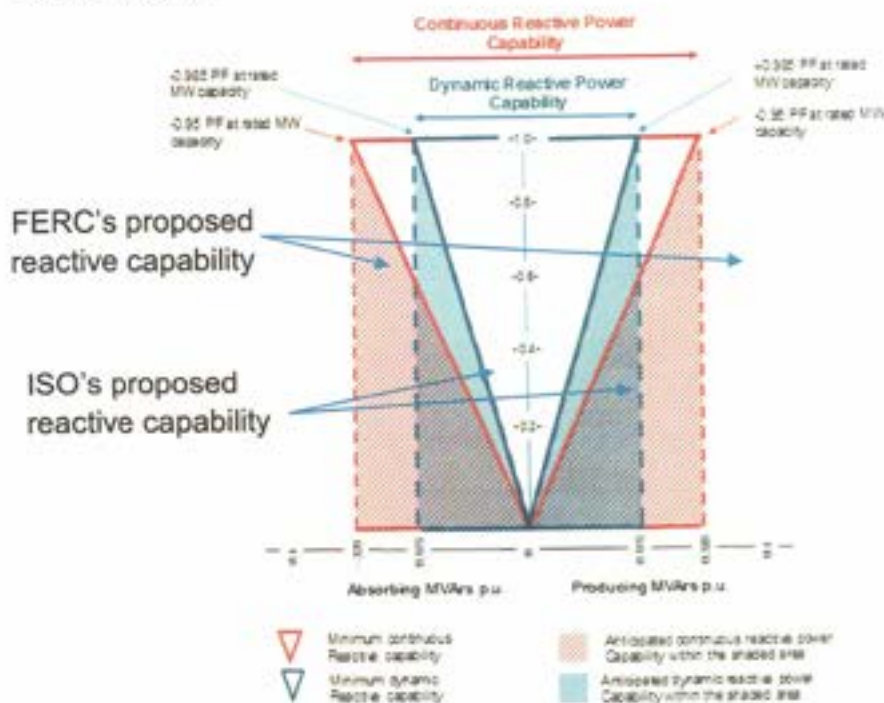
The primary objective of this test is to demonstrate the capability of the plant to operate in voltage regulation mode within a power factor range of 0.95 leading/lagging. The plant controller maintains the specified voltage set point at the high side of the generator step-up bank by regulating the reactive power produced by the inverters.

### **Test Procedure**

The ISO would test the plant at *three* different real power output levels: (1) maximum production during the middle of the day, (2) during sunset when the plant is at approximately 50% of its maximum capability, and (3) during sunset when the plant is close to zero production. The ISO

will test the plant's reactive power capability to absorb and produce reactive power in accordance with Figure A-1, within a range of  $\pm 100$  MVAR during various levels of real power output.

- The plant would first be tested at its maximum real power output for a given irradiance level. At maximum real power output, the plant must demonstrate that it can produce approximately 33% of real output as dynamic reactive. Similarly, at maximum real power output, the plant must demonstrate that it can absorb approximately 33% of its real power output as reactive output.
- During sunset, as the solar production drops off to approximately 50% of the resource's maximum capability, the plant must demonstrate that it can produce and absorb approximately 33% of its real power output as dynamic reactive output.
- During sunset, as the plant production approaches zero MW, the plant must demonstrate that it can produce and absorb approximately 33% of its real power output as dynamic reactive output.



**Figure A-1. Reactive power capability at the POI. Illustration from NREL**

Note: The red vertical lines shown in Figure A-1 represent the expected reactive capability of the asynchronous generating plant at the high side of the generator step-up bank. At all levels of real power output, the plant is expected to produce or absorb reactive power equivalent to approximately 33% of the plant's actual real power output. For example, at the plant's maximum real power capability, the expected reactive capability should be 33 MVARs lagging or 33 MVARs leading. Also, at zero real power output, the expected dynamic reactive capability should be zero MVARs lagging or zero MVARs leading.

### Expectation

The plant must demonstrate that its reactive capability follow FERC's proposed reactive capability, as shown in Figure A-1.

### Curtailment

None.

### Active Power Control Capabilities

CAISO seeks to test the APC capability to assess the plant's ability to control its output in specific increments by being able to mimic a specified ramp rate. The results of this test would be used to determine the plant's ability to provide ancillary services such as spinning reserve and nonspinning reserve.

### Objective

This objective of this test is to demonstrate that the plant can decrease output or increase output while maintaining a specific ramp rate.

### Test Procedure

This test is similar to starting up and shutting down the plant in a coordinated and controllable manner. The test would be done at *two different ramp rates*.

- The plant would be instructed to reduce its output to three different set points (*not to exceed 60 MW*) at a predetermined ramp rate, as shown in Figure A-2.
- The plant would then be instructed to ramp back up to full production following predefined set points at the predetermined ramp rate, as shown in Figure A-2.
- Repeat the above test using a different ramp rate.

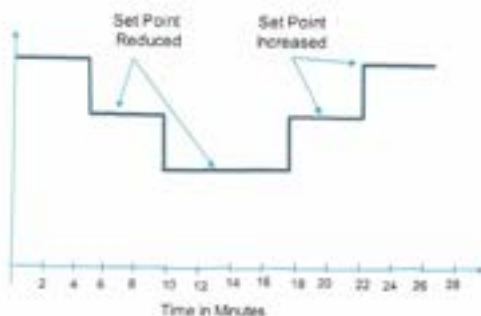


Figure A-2. Increase/decrease output at a specified ramp rate. *Illustration from CAISO*

### Expectation

The plant must demonstrate its capability to move from its current set point to a desired set point at a specified ramp rate.

### Curtailment

It is expected that the plant would be curtailed up to 60 MW for a period of 60 minutes.

### Frequency Response

The frequency response capability would entail two separate tests: (1) a droop test and (2) a frequency response test.

The definition of implemented frequency droop control for PV plant is the same as that for conventional generators:

$$Droop = \frac{\Delta P / P_{rated}}{\Delta f / 60 \text{ Hz}}$$

The plant's rated power (299.9 MW) is used in the above equation from the droop setting calculation. The plant should adjust its power output in accordance with the droop curve with a symmetric deadband, as shown in Figure A-3. The upper limit of the droop curve is the available plant power based on the current level of solar irradiance and panel temperatures.

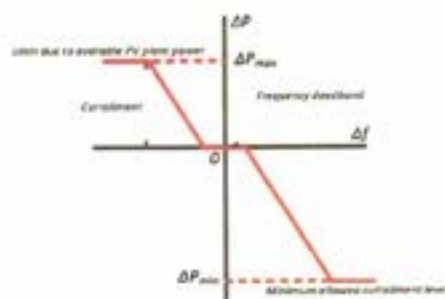


Figure A-3. Frequency droop explained. Illustration from NREL

### Frequency Droop Test (Capability to Provide Spinning Reserve)

#### Objective

The objective of this test is to demonstrate that the plant can provide a response in accordance with the 5% and 3% droop settings through its governor-like control system. The plant would be instructed to operate *below its maximum capability during both tests*.

#### Test Procedure

For the first test, the plant would be instructed to operate at *20 MW below its maximum capability*. This test would be done using a 5% droop and a deadband of  $\pm 0.036$  Hz.

- The ISO would test the frequency droop capability of the plant by using an actual underfrequency event that occurred in the Western Interconnection during the past year. The underfrequency event data set (*approximately 10 minutes of data*) would be fed into the plant's controller, and the plant response would then be monitored.
- The frequency droop capability would be demonstrated using one actual high-frequency time series data set provided by NREL. Examples of underfrequency and overfrequency event time series measured by NREL are shown in Figure A-4 and Figure A-5, respectively.

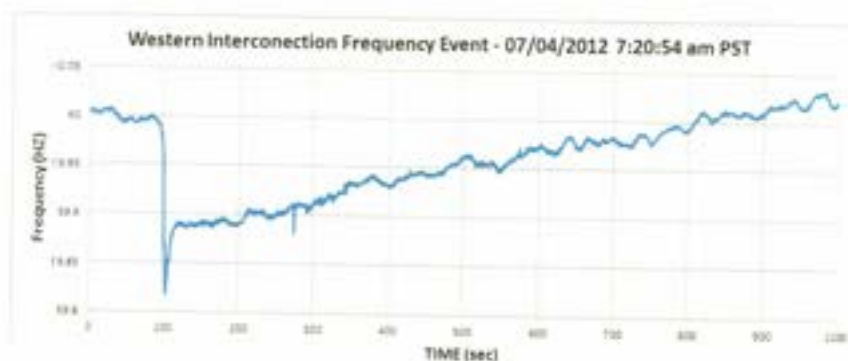


Figure A-4. Example of an underfrequency event. *Illustration from NREL*



Figure A-5. Example of an overfrequency event. *Illustration from NREL*

- The frequency event time series data will be used by the power plant controller to trigger the droop response by the plant.
- The above test would be repeated with the plant at 20 MW below its maximum capability. This test would be done using a 3% droop and a deadband of  $\pm 0.036$  Hz.

#### Expectation

Through the action of the governor-like control system, the plant must respond automatically within 1 second in proportion to the frequency deviations outside the deadband.

#### Curtailment

It is expected that the plant would be curtailed by 30 MW for approximately 60 minutes.

#### Capability to Provide Frequency Response

##### Objective

The objective of this test is to demonstrate that the plant can provide frequency response consistent with the North American Electric Reliability Corporation's BAL-003-1.

##### Test Procedure

- The plant would be instructed to operate 20 MW below its maximum capability before applying a step change of rapid frequency decline. An actual frequency event (approximately 10 minutes) would be fed into the plant's controller, and the plant's response would be monitored. This test may require tuning a delay in response to ensure

that the frequency response occurs within 20–52 seconds following the step change in frequency.

- The plant *does not have headroom* and can only reduce output in response to large frequency deviations below the scheduled frequency. The test would entail feeding the plant controller with a frequency more than 0.036 Hz above scheduled frequency.
- Repeat the above test with the plant operating 40 MW below its capability for a given irradiance level.

#### *Expectation*

Through the action of the governor-like control system, the plant must respond automatically in proportion to frequency deviations.

#### *Curtailment*

It is expected that the plant would be curtailed by 20 MW for 60 minutes and by 40 MW for 60 minutes.

